

1-2014

Nonstorm time dynamics of electron radiation belts observed by the Van Allen Probes

Zhenpeng Su

University of Science and Technology of China

Fuliang Xiao

Changsha University of Electric Power

Huinan Zheng

University of Science and Technology of China

Zhaoguo He

Chinese Academy of Sciences, Beijing

Hui Zhu

University of Science and Technology of China

See next page for additional authors

Follow this and additional works at: https://scholars.unh.edu/physics_facpub



Part of the [Physics Commons](#)

Recommended Citation

Su, Z., et al. (2014), Nonstorm time dynamics of electron radiation belts observed by the Van Allen Probes, *Geophys. Res. Lett.*, 41, 229–235, doi:10.1002/2013GL058912.

This Article is brought to you for free and open access by the Physics at University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Physics Scholarship by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact nicole.hentz@unh.edu.

Authors

Zhenpeng Su, Fuliang Xiao, Huinan Zheng, Zhaoguo He, Hui Zhu, Min Zhang, Chao Shen, Yuming Wang, Shui Wang, C A. Kletzing, W. S. Kurth, G. B. Hospodarsky, Harlan E. Spence, Geoffrey Reeves, H. O. Funsten, J. B. Blake, and D. N. Baker

RESEARCH LETTER

10.1002/2013GL058912

Special Section:

Early Results From the Van Allen Probes

Key Points:

- A rarely reported nonstorm time event of RB reformation observed by RBSP
- Formation of a new belt near the outer boundary of the original outer belt
- Importance of chorus-driven local acceleration: observation and simulation

Correspondence to:

Z. Su,
szpe@mail.ustc.edu.cn

Citation:

Su, Z., et al. (2014), Nonstorm time dynamics of electron radiation belts observed by the Van Allen Probes, *Geophys. Res. Lett.*, 41, 229–235, doi:10.1002/2013GL058912.

Received 1 DEC 2013

Accepted 24 DEC 2013

Accepted article online 3 JAN 2014

Published online 22 JAN 2014

Nonstorm time dynamics of electron radiation belts observed by the Van Allen Probes

Zhenpeng Su^{1,2}, Fuliang Xiao³, Huinan Zheng^{1,2}, Zhaoguo He⁴, Hui Zhu^{1,2}, Min Zhang^{5,1}, Chao Shen⁶, Yuming Wang^{1,2}, Shui Wang¹, C. A. Kletzing⁷, W. S. Kurth⁷, G. B. Hospodarsky⁷, H. E. Spence⁸, G. D. Reeves⁹, H. O. Funsten¹⁰, J. B. Blake¹¹, and D. N. Baker¹²
¹CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, University of Science and Technology of China, Hefei, China, ²State Key Laboratory of Space Weather, Chinese Academy of Sciences, Beijing, China, ³School of Physics and Electronic Sciences, Changsha University of Science and Technology, Changsha, China, ⁴Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing, China, ⁵Department of Mathematics and Physics, Anhui University of Architecture, Hefei, China, ⁶State Key Laboratory of Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing, China, ⁷Department of Physics and Astronomy, University of Iowa, Iowa, Iowa, USA, ⁸Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA, ⁹Space Science and Applications Group, Los Alamos National Laboratory, Los Alamos, New Mexico, USA, ¹⁰ISR Division, Los Alamos National Laboratory, Los Alamos, New Mexico, USA, ¹¹The Aerospace Corporation, Los Angeles, California, USA, ¹²Laboratory for Atmospheric and Space Research, University of Colorado Boulder, Boulder, Colorado, USA

Abstract Storm time electron radiation belt dynamics have been widely investigated for many years. Here we present a rarely reported nonstorm time event of electron radiation belt evolution observed by the Van Allen Probes during 21–24 February 2013. Within 2 days, a new belt centering around $L = 5.8$ formed and gradually merged with the original outer belt, with the enhancement of relativistic electron fluxes by a factor of up to 50. Strong chorus waves (with power spectral density up to 10^{-4} nT²/Hz) occurred in the region $L > 5$. Taking into account the local acceleration driven by these chorus waves, the two-dimensional STEERB can approximately reproduce the observed energy spectrums at the center of the new belt. These results clearly illustrate the complexity of electron radiation belt behaviors and the importance of chorus-driven local acceleration even during the nonstorm times.

1. Introduction

The Van Allen radiation belts normally comprise two distinct zones of geomagnetically trapped particles spatially separated by the slot region. The inner radiation belt is populated by both energetic electrons (~ 100 keV) and positive ions (~ 100 MeV), which is quite stable over time scales of years to decades. The outer radiation belt is populated by energetic electrons (~ 100 keV), which is highly dynamic over time scales of minutes to days. Benefiting from the growing network of satellites since the 1990s, the global and complex radiation belt dynamics have been revealed. Many storm-related events on 9 October 1990 [e.g., Brautigam and Albert, 2000; Summers et al., 2002; Horne et al., 2003; Thorne et al., 2007; Albert et al., 2009; Su et al., 2011], 24 March 1991 [e.g., Blake et al., 1992; Li et al., 1993; Hudson et al., 1997], 10 January 1997 [Reeves et al., 1998], 28 October 2003 [e.g., Horne et al., 2005b; Shprits et al., 2006], 1 September 2012 [e.g., Baker et al., 2013b; Thorne et al., 2013; Shprits et al., 2013], and 8 October 2012 [Reeves et al., 2013] have been extensively investigated. However, relatively few events during nonstorm times have been studied. Meredith et al. [2002] analyzed the dropout and buildup of outer zone energetic electron fluxes associated with prolonged substorm activity (but weak storm activity) during 11–16 September 1990. Park et al. [2010] presented some correlated observations on the slot region injection during a nonstorm time substorm on 24 February 2004. In particular, however, simultaneous observation and corresponding simulation regarding nonstorm time radiation belt dynamics are rarely reported.

An important challenge of radiation belt research is to resolve the precise mechanism for the acceleration of relativistic (\sim MeV) electrons. There are two leading acceleration mechanisms: (1) inward radial diffusion enhanced by the drift resonance of ULF waves [Elkington et al., 1999; Zong et al., 2007] and (2) local acceleration driven by the gyroresonance of VLF waves [e.g., Horne and Thorne, 1998; Summers et al., 1998, 2002; Thorne, 2010]. Recently, numerous observations [e.g., Green and Kivelson, 2004; Horne et al., 2005b;

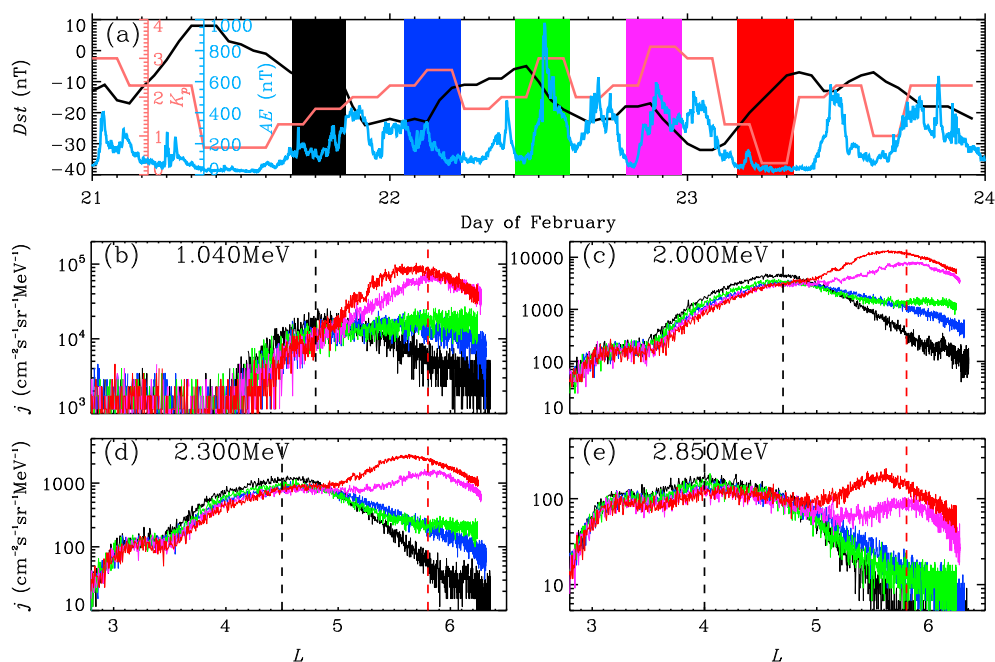


Figure 1. Overview of the nonstorm time event of radiation belt evolution: (a) geomagnetic activity indices Dst , K_p , and AE obtained from the CDAWeb database; (b–e) radial profiles of spin-averaged relativistic electron fluxes at energies $E_k = 1.040$ MeV, 2.000 MeV, 2.300 MeV, and 2.850 MeV, observed by the ECT instrument on board RBSP-B satellite during its outbound passes of five continuous orbits (indicated by five different colors). The black and red vertical dashed lines approximately denote the centers of original and new radiation belts.

Chen et al., 2007] and simulations [e.g., Shprits et al., 2006; Albert et al., 2009; Su et al., 2010] have shown the evidence for the dominance of local acceleration during geomagnetic storms.

In this letter, we report a nonstorm time event of electron radiation belt evolution observed by the recently launched Van Allen Radiation Belt Storm Probes (RBSP) [Mauk et al., 2012] in late February 2013 and further identify a potentially dominant acceleration mechanism through the combination of observations and simulations.

2. Radiation Belt Dynamics

Figure 1 gives an overview of this radiation belt reformation event from 21 to 24 February 2013. The geomagnetic activity indices Dst , K_p , and AE are obtained from the coordinated data analysis web (CDAWeb) database (<http://cdaweb.gsfc.nasa.gov/>), and the radial profiles of spin-averaged relativistic electron fluxes at the selected energy channels are observed by the Energetic Particle, Composition, and Thermal Plasma (ECT) instrument [Spence et al., 2013] on board RBSP-B satellite. Our study primarily covers five continuous orbits of RBSP-B satellite (orbital period ~ 9.5 h), and the corresponding outbound passes are denoted by the colored shadows. During this period, both the Dst and K_p indices showed slow fluctuations in relatively limited ranges ($-35\text{ nT} \leq Dst \leq 10\text{ nT}$ and $0 \leq K_p \leq 3.33$), indicating the nonstorm state of magnetosphere. However, the AE index (with maximum value ~ 1000 nT) was predominantly enhanced, indicating the occurrence of prolonged substorm activity. In the first orbit (black lines), the outer zone fluxes peaked in the range $L = 4.0$ – 5.0 (depending on the electron energy) with the outer boundary $L \approx 6.0$. In the following four orbits, the outer zone fluxes gradually exhibited a new peak around $L = 5.8$ but had tiny changes in the spatial range $L = 2.5$ – 5.0 . Within 2 days, the relativistic electron fluxes at $L = 5.8$ increased by a factor of up to 50. In the fifth orbit (red lines), the peak location of outer zone electron fluxes at the energies $E_k = 1.040$, 2.000, and 2.300 MeV thoroughly moved to $L \approx 5.8$, while two peaks (at $L \approx 4.0$ and 5.8) coexisted at the energy $E_k = 2.850$ MeV.

The current phenomenon can be interpreted as the gradual emergence of new radiation belt (centering around $L = 5.8$) and the simultaneous merging with the original radiation belt (centering at $L = 4.0$ – 5.0). The present nonstorm time “new belt” located near the outer boundary of original belt was identified at the

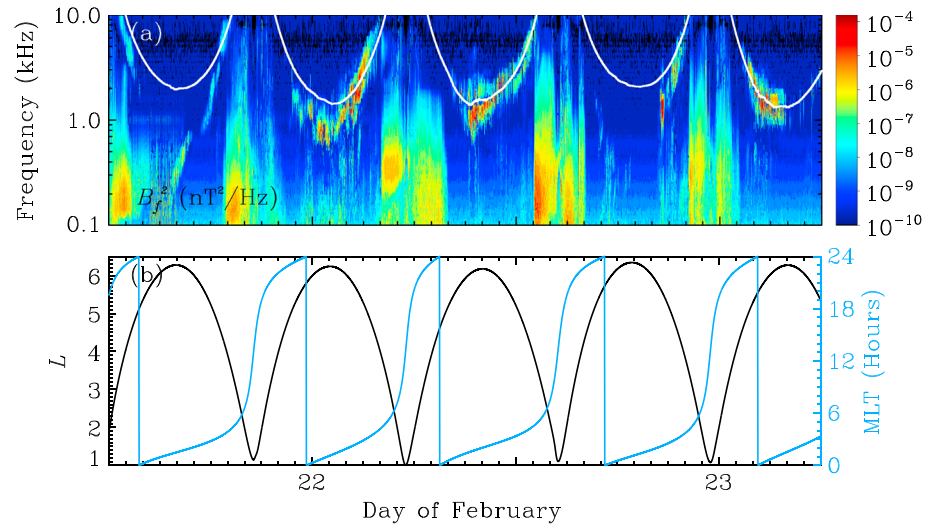


Figure 2. (a) Magnetic power spectral density B_f^2 in the frequency range of 0.1 to 10.0 kHz observed by the EMFISIS instrument on board the RBSP-A satellite, where the white line represents one half the electron gyrofrequency; (b) corresponding values of L and MLT for the RBSP-A satellite.

energies $E_k < 3.0$ MeV. Some storm-related events of “new radiation belt” formation have also been reported [e.g., Blake *et al.*, 1992; Shprits *et al.*, 2006; Baker *et al.*, 2013b]. These storm time “new belts” located around $L = 3$ were spatially separated from (instead of merging with) the other belts at the energies $E_k = 2 - 6$ MeV or higher. Different physical mechanisms have been proposed to explain these storm time events: The 24 March 1991 event [Blake *et al.*, 1992] was caused by the impulsive injection of electrons [Li *et al.*, 1993]; the 28 October 2003 event [Shprits *et al.*, 2006] mainly resulted from the chorus-driven local acceleration; and the 1 September 2012 event [Baker *et al.*, 2013b] was largely produced by the loss of a distant portion of the outer zone electrons. For this nonstorm time event, the strength of radial diffusion (evaluated from the K_p dependent expressions [Brautigam and Albert, 2000]) may be relatively weak. In fact, we have checked that ULF waves had no significant enhancement throughout this event (compared to those ULF waves before the event). Hence, radial diffusion may contribute little to the acceleration of relativistic electrons, especially in the heart of new belt. Further, considering the evolution time scale of the event (~ 2 days), local acceleration by VLF waves was the most promising physical mechanism.

3. Relativistic Electron Acceleration

Figure 2 presents the distribution of magnetic power spectral density B_f^2 in the frequency range of 0.1 to 10.0 kHz observed by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrument [Kletzing *et al.*, 2013] on board the RBSP-A satellite, and the variation of corresponding satellite locations (L and MLT). The magnetic latitudes of satellite were restricted in the range $|\lambda| \leq 21^\circ$ [Mauk *et al.*, 2012]. Strong chorus waves (with power spectral density up to $10^{-4} \text{ nT}^2/\text{Hz}$) can be clearly identified around the white line (one half the electron gyrofrequency), which primarily occurred in the nightside (MLT $\approx 0-6$) and at the large L -shell region ($L \gtrsim 5$). Note that the similar chorus wave characteristics can also be observed by the RBSP-B satellite.

We next determine the chorus-driven buildup of radiation belt electron fluxes at $L = 5.8$ (the center of new belt) using the two-dimensional storm-time evolution of electron radiation belt (STEERB) code [Xiao *et al.*, 2009; Su *et al.*, 2010], which is based on the solution of Fokker-Planck equation for electron phase space density (PSD) f evolution

$$\begin{aligned} \frac{\partial f}{\partial t} = & \frac{1}{G} \frac{\partial}{\partial \alpha_e} \left[G \left(\langle D_{aa} \rangle \frac{\partial f}{\partial \alpha_e} + \langle D_{ap} \rangle \frac{\partial f}{\partial p} \right) \right] \\ & + \frac{1}{G} \frac{\partial}{\partial p} \left[G \left(\langle D_{pa} \rangle \frac{\partial f}{\partial \alpha_e} + \langle D_{pp} \rangle \frac{\partial f}{\partial p} \right) \right] - \frac{f}{\tau_L}, \end{aligned} \quad (1)$$

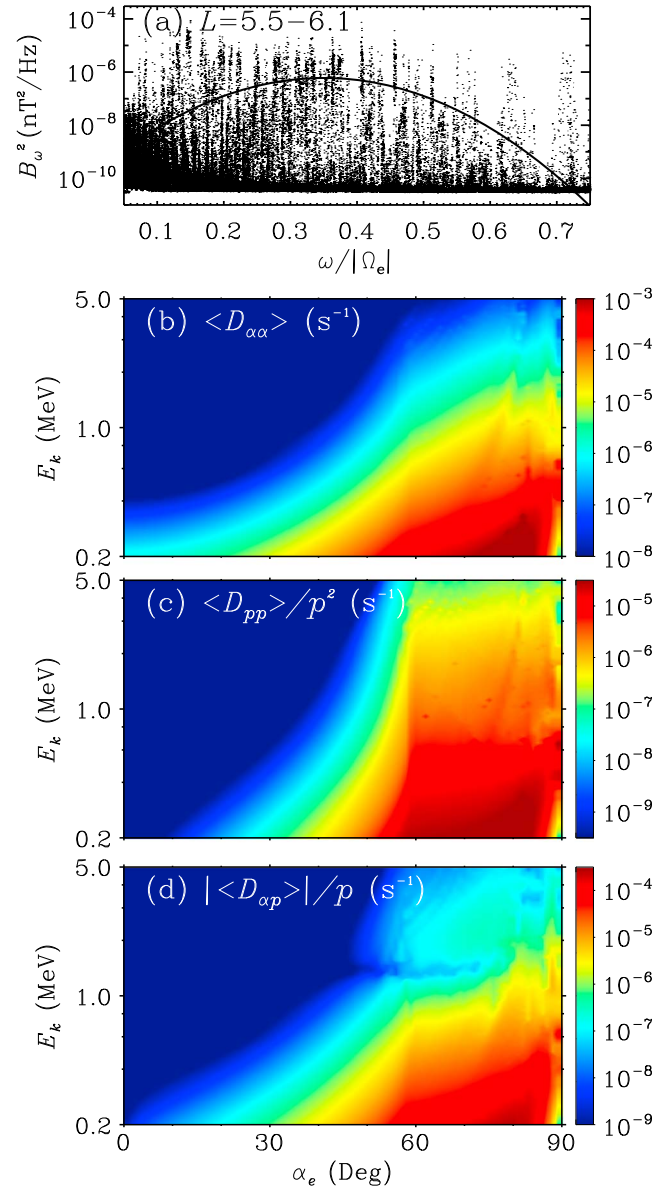


Figure 3. (a) Observed magnetic power spectral density $B_\omega^2 = B_f^2/2\pi$ in the spatial range $L = 5.8 \pm 0.3$ of five continuous orbits (dots) and modeled Gauss-type power spectral density distribution (line); (b-d) two-dimensional distributions of bounce-averaged diffusion coefficients as functions of pitch angle α_e and kinetic energy E_k for modeled chorus waves at $L = 5.8$.

with

$$G = p^2 T(\alpha_e) \sin \alpha_e \cos \alpha_e, \quad (2)$$

$$T(\alpha_e) \approx 1.30 - 0.56 \sin \alpha_e. \quad (3)$$

Here $\langle D_{\alpha\alpha} \rangle$, $\langle D_{pp} \rangle$, and $\langle D_{\alpha p} \rangle = \langle D_{p\alpha} \rangle$ are the drift and bounce-averaged diffusion coefficients in the equatorial pitch angle α_e , momentum p , and cross terms, depending on the wave spectral and normal angle distributions, as well as the ratio between plasma frequency ω_{pe} and equatorial electron gyrofrequency $|\Omega_e|$; τ_L is the electron lifetime, which is assumed to be infinite out of the loss cone and be a quarter of bounce period in the loss cone.

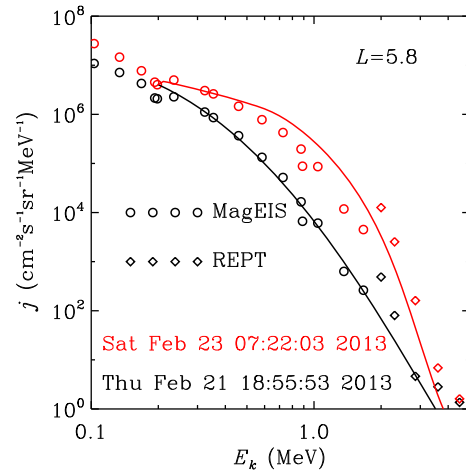


Figure 4. Initial (black) and final (red) energy spectrums at $L = 5.8$ observed by RBSP-B satellite (circles for MagEIS and diamonds for REPT) and simulated by STEERB model (lines).

is also assumed to obey the typical Gauss-type distribution with a center $\theta_m = 0^\circ$, a half width $\Delta\theta = 15^\circ$, a lower cutoff $\theta_1 = 0^\circ$, and an upper cutoff $\theta = 45^\circ$. These waves are further assumed to spread in the spatial range $|\lambda| \leq 15^\circ$ and $0 \leq \text{MLT} \leq 6$. Note that these wave parameters are similar to those of nightside chorus wave model [e.g., Horne et al., 2005a; Li et al., 2007; Ni et al., 2008; Albert et al., 2009]. The ratio $\omega_{pe}/|\Omega_e|$ is set to be 4.6 based on the dipolar model and the electron density model of Carpenter and Anderson [1992]. Figures 3b–3d show the distribution of calculated bounce-averaged diffusion coefficients in the range of $0^\circ \leq \alpha_{eq} \leq 90^\circ$ and $0.2 \text{ MeV} \leq E_k \leq 5.0 \text{ MeV}$, comparable to the previous calculations [e.g., Li et al., 2007; Summers et al., 2007; Albert et al., 2009].

The initial PSD is specified as a kappa-type distribution

$$f(\alpha_e, E_k)|_{t=0} = C \frac{E_k}{p^2} \left(1 + \frac{E_k}{\kappa E_0} \right)^{-\kappa-1} \sin^n \alpha_e, \quad (4)$$

where C is a constant, $\kappa = 9$ and $E_0 = 0.05 \text{ MeV}$ are chosen to fit the observed energy spectrum, $n = 2$ is the pitch angle index at $L = 5.8$ [see Thorne et al., 2005]. The boundary conditions are set to be

$$\left. \frac{\partial f}{\partial \alpha_e} \right|_{\alpha_e=0^\circ} = \left. \frac{\partial f}{\partial \alpha_e} \right|_{\alpha_e=90^\circ} = 0, \quad (5)$$

$$f|_{E_k=0.2 \text{ MeV}} = \text{constant}, \quad f|_{E_k=5.0 \text{ MeV}} = \text{constant} \quad (6)$$

The comparison between RBSP-B-observed and STEERB-simulated energy spectrums around $L = 5.8$ is presented in Figure 4. The spectrums observed by ECT-Magnetic Electron Ion Spectrometer (MagEIS) and ECT-Relativistic Electron Proton Telescope (REPT) had a mismatch around $E_k = 2.0 \text{ MeV}$, which was caused by the difference in response functions at the high-energy end of MagEIS [Blake et al., 2013] and the low-energy end of REPT [Baker et al., 2013a]. We generally trust the MagEIS data in the low-energy ($\sim < 2.0 \text{ MeV}$) range and the REPT data in the high-energy ($\sim > 2.0 \text{ MeV}$) range. In the first orbit (black), the simulations agree well with the observations except around the energy $E_k = 2.0 \text{ MeV}$. In the fifth orbit (red), the simulations basically reflect the observed characteristics of energy spectrum, suggesting that the chorus waves substantially accounted for the nonstorm time buildup of radiation belt electron fluxes. It should be noted that, compared to the observations, the simulations indeed show some overestimation at the low energies ($\sim 0.4\text{--}1.5 \text{ MeV}$) and underestimation at the high energies ($\sim 1.5\text{--}3.0 \text{ MeV}$), which may be caused by the inaccuracy of wave model constructed based on limited observations.

4. Conclusions and Discussions

Storm time electron radiation belt dynamics have been widely investigated for many years, and the strength of storm has been found to possess poor correlation with the net changes of energetic electron fluxes [Reeves *et al.*, 2003]. Here we report a nonstorm time event of electron radiation belt evolution observed by the Van Allen Probes from 21 to 24 February 2013. Within 2 days, a new belt centering around $L = 5.8$ (near the outer boundary of the original outer belt) formed and gradually merged with the original belt. In the region $L > 5$, the relativistic electron fluxes increased by a factor of up to 50. These results clearly illustrate that the electron radiation belt can exhibit dramatic variabilities not only during storm times but also during nonstorm times and that the radiation belt environment should be closely monitored for the space weather applications even in nonstorm times.

We further identify a potential acceleration mechanism responsible for the current nonstorm time enhancement of energetic electron fluxes through the quantitative comparison between STEERB simulations and RBSP observations. In the region $L \sim 5$, strong chorus waves (with power spectral density up to $10^{-4} \text{ nT}^2/\text{Hz}$) were observed. The modeled wave parameters are input into the two-dimensional STEERB code to determine chorus-driven electron radiation belt evolution at $L = 5.8$. In about 2 days, the energy spectrums simulated by STEERB model are found to show reasonable agreement with those observed by RBSP-B satellite, suggesting that the local acceleration by chorus waves was the dominant acceleration mechanism for this nonstorm time event.

Acknowledgments

We acknowledge J.H. King, N. Papashvili, and CDAWeb for the use of Dst , K_p , and AE data. This work was supported by the National Natural Science Foundation of China grants 41274169, 41274174, 41174125, 41131065, 41121003, 41074120, 41231066, and 41304134, the Chinese Academy of Sciences grants KZCX2-EW-QN510 and KZZD-EW-01-4, the National Key Basic Research Special Foundation of China grant 2011CB811403, the Strategic Priority Research Program on Space Science of the Chinese Academy of Sciences grant XDA04060201, and the Fundamental Research Funds for the Central Universities WK2080000031.

The Editor thanks James McCullough and an anonymous reviewer for their assistance in evaluating this paper.

References

- Albert, J. M., N. P. Meredith, and R. B. Horne (2009), Three-dimensional diffusion simulation of outer radiation belt electrons during the October 9, 1990, magnetic storm, *J. Geophys. Res.*, **114**, A09214, doi:10.1029/2009JA014336.
- Baker, D. N., et al. (2013a), The relativistic electron-proton telescope (REPT) instrument on board the radiation belt storm probes (RBSP) spacecraft: Characterization of Earth's radiation belt high-energy particle populations, *Space Sci. Rev.*, **179**, 337–381, doi:10.1007/s11214-012-9950-9.
- Baker, D. N., et al. (2013b), A long-lived relativistic electron storage ring embedded in Earth's outer Van Allen belt, *Science*, **340**(6129), 186–190.
- Blake, J. B., W. A. Kolasinski, R. W. Fillius, and E. G. Mullen (1992), Injection of electrons and protons with energies of tens of MeV into L less than 3 on 24 March 1991, *Geophys. Res. Lett.*, **19**, 821–824, doi:10.1029/92GL00624.
- Blake, J. B., et al. (2013), The magnetic electron ion spectrometer (MagEIS) instruments aboard the radiation belt storm probes (RBSP) spacecraft, *Space Sci. Rev.*, **179**, 383–421, doi:10.1007/s11214-013-9991-8.
- Brautigam, D. H., and J. M. Albert (2000), Radial diffusion analysis of outer radiation belt electrons during the October 9, 1990, magnetic storm, *J. Geophys. Res.*, **105**, 291–310, doi:10.1029/1999JA900344.
- Carpenter, D. L., and R. R. Anderson (1992), An ISEE/whistler model of equatorial electron density in the magnetosphere, *J. Geophys. Res.*, **97**, 1097–1108.
- Chen, Y., G. D. Reeves, and R. H. W. Friedel (2007), The energization of relativistic electrons in the outer Van Allen radiation belt, *Nat. Phys.*, **3**, 614–617, doi:10.1038/nphys565.
- Elkington, S. R., M. K. Hudson, and A. A. Chan (1999), Acceleration of relativistic electrons via drift-resonant interaction with toroidal-mode Pc-5 ULF oscillations, *Geophys. Res. Lett.*, **26**, 3273–3276, doi:10.1029/1999GL003659.
- Green, J. C., and M. G. Kivelson (2004), Relativistic electrons in the outer radiation belt: Differentiating between acceleration mechanisms, *J. Geophys. Res.*, **109**, A03213, doi:10.1029/2003JA010153.
- Horne, R. B., and R. M. Thorne (1998), Potential waves for relativistic electron scattering and stochastic acceleration during magnetic storms, *Geophys. Res. Lett.*, **25**, 3011–3014, doi:10.1029/98GL01002.
- Horne, R. B., N. P. Meredith, R. M. Thorne, D. Heynderickx, R. H. A. Iles, and R. R. Anderson (2003), Evolution of energetic electron pitch angle distributions during storm time electron acceleration to megaelectronvolt energies, *J. Geophys. Res.*, **108**(A1), 1016, doi:10.1029/2001JA009165.
- Horne, R. B., R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R. Anderson (2005a), Timescale for radiation belt electron acceleration by whistler mode chorus waves, *J. Geophys. Res.*, **110**, A03225, doi:10.1029/2004JA010811.
- Horne, R. B., et al. (2005b), Wave acceleration of electrons in the Van Allen radiation belts, *Nature*, **437**, 227–230, doi:10.1038/nature03939.
- Hudson, M. K., S. R. Elkington, J. G. Lyon, V. A. Marchenko, I. Roth, M. Temerin, J. B. Blake, M. S. Gussenhoven, and J. R. Wygant (1997), Simulations of radiation belt formation during storm sudden commencements, *J. Geophys. Res.*, **102**, 14,087–14,102, doi:10.1029/97JA03995.
- Kletzing, C. A., et al. (2013), The Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) on RBSP, *Space Sci. Rev.*, **179**(1–4), 127–181, doi:10.1007/s11214-013-9993-6.
- Li, W., Y. Y. Shprits, and R. M. Thorne (2007), Dynamic evolution of energetic outer zone electrons due to wave-particle interactions during storms, *J. Geophys. Res.*, **112**, A10220, doi:10.1029/2007JA012368.
- Li, X., I. Roth, M. Temerin, J. R. Wygant, M. K. Hudson, and J. B. Blake (1993), Simulation of the prompt energization and transport of radiation belt particles during the March 24, 1991 SSC, *Geophys. Res. Lett.*, **20**, 2423–2426, doi:10.1029/93GL02701.
- Mauk, B. H., N. J. Fox, S. G. Kanekal, R. L. Kessel, D. G. Sibeck, and A. Ukhorskiy (2012), Science objectives and rationale for the Radiation Belt Storm Probes mission, *Space Sci. Rev.*, **179**(1–4), 3–27, doi:10.1007/s11214-012-9908-y.
- Meredith, N. P., R. B. Horne, R. H. A. Iles, R. M. Thorne, D. Heynderickx, and R. R. Anderson (2002), Outer zone relativistic electron acceleration associated with substorm-enhanced whistler mode chorus, *J. Geophys. Res.*, **107**(A7), 1144, doi:10.1029/2001JA900146.
- Ni, B., R. M. Thorne, Y. Y. Shprits, and J. Bortnik (2008), Resonant scattering of plasma sheet electrons by whistler-mode chorus: Contribution to diffuse auroral precipitation, *Geophys. Res. Lett.*, **35**, L11106, doi:10.1029/2008GL034032.

- Park, J., et al. (2010), Non-stormtime injection of energetic particles into the slot-region between Earth's inner and outer electron radiation belts as observed by STSAT-1 and NOAA-POES, *Geophys. Res. Lett.*, **37**, L16102, doi:10.1029/2010GL043989.
- Reeves, G. D., K. L. McAdams, R. H. W. Friedel, and T. P. O'Brien (2003), Acceleration and loss of relativistic electrons during geomagnetic storms, *Geophys. Res. Lett.*, **30**(10), 1529, doi:10.1029/2002GL016513.
- Reeves, G. D., et al. (1998), The global response of relativistic radiation belt electrons to the January 1997 magnetic cloud, *Geophys. Res. Lett.*, **25**, 3265–3268, doi:10.1029/98GL02509.
- Reeves, G. D., et al. (2013), Electron acceleration in the heart of the Van Allen radiation belts, *Science*, **341**(6149), 991–994.
- Shprits, Y. Y., R. M. Thorne, R. B. Horne, S. A. Glauert, M. Cartwright, C. T. Russell, D. N. Baker, and S. G. Kanekal (2006), Acceleration mechanism responsible for the formation of the new radiation belt during the 2003 halloween solar storm, *Geophys. Res. Lett.*, **33**, L05104, doi:10.1029/2005GL024256.
- Shprits, Y. Y., D. Subbotin, A. Drozdov, M. E. Usanova, A. Kellerman, K. Orlova, D. N. Baker, D. L. Turner, and K.-C. Kim (2013), Unusual stable trapping of the ultra-relativistic electrons in the Van Allen radiation belts, *Nat. Phys.*, **9**, 699–703, doi:10.1038/nphys2760.
- Spence, H. E., et al. (2013), Science goals and overview of the energetic particle, composition, and thermal plasma (ECT) suite on NASA's Radiation Belt Storm Probes (RBSP) mission, *Space Sci. Rev.*, **179**(1–4), 311–336, doi:10.1007/s11214-013-0007-5.
- Su, Z., F. Xiao, H. Zheng, and S. Wang (2010), STEERB: A three-dimensional code for storm-time evolution of electron radiation belt, *J. Geophys. Res.*, **115**, A09208, doi:10.1029/2009JA015210.
- Su, Z., F. Xiao, H. Zheng, and S. Wang (2011), CRRES observation and STEERB simulation of the 9 October 1990 electron radiation belt dropout event, *Geophys. Res. Lett.*, **38**, L06106, doi:10.1029/2011GL046873.
- Summers, D., R. M. Thorne, and F. Xiao (1998), Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the magnetosphere, *J. Geophys. Res.*, **103**, 20,487–20,500.
- Summers, D., C. Ma, N. P. Meredith, R. B. Horne, R. M. Thorne, D. Heynderickx, and R. R. Anderson (2002), Model of the energization of outer-zone electrons by whistler-mode chorus during the October 9, 1990 geomagnetic storm, *Geophys. Res. Lett.*, **29**(24), 2174, doi:10.1029/2002GL016039.
- Summers, D., B. Ni, and N. P. Meredith (2007), Timescales for radiation belt electron acceleration and loss due to resonant wave-particle interactions: 2. Evaluation for VLF chorus, ELF hiss, and electromagnetic ion cyclotron waves, *J. Geophys. Res.*, **112**, A04207, doi:10.1029/2006JA011993.
- Thorne, R. M. (2010), Radiation belt dynamics: The importance of wave-particle interactions, *Geophys. Res. Lett.*, **37**, L22107, doi:10.1029/2010GL044990.
- Thorne, R. M., T. P. O'Brien, Y. Y. Shprits, D. Summers, and R. B. Horne (2005), Timescale for MeV electron microburst loss during geomagnetic storms, *J. Geophys. Res.*, **110**, A09202, doi:10.1029/2004JA010882.
- Thorne, R. M., Y. Y. Shprits, N. P. Meredith, R. B. Horne, W. Li, and L. R. Lyons (2007), Refilling of the slot region between the inner and outer electron radiation belts during geomagnetic storms, *J. Geophys. Res.*, **112**, A06203, doi:10.1029/2006JA012176.
- Thorne, R. M., et al. (2013), Evolution and slow decay of an unusual narrow ring of relativistic electrons near $L \sim 3.2$ following the September 2012 magnetic storm, *Geophys. Res. Lett.*, **40**, 3507–3511, doi:10.1002/grl.50627.
- Xiao, F., Z. Su, H. Zheng, and S. Wang (2009), Modeling of outer radiation belt electrons by multidimensional diffusion process, *J. Geophys. Res.*, **114**, A03201, doi:10.1029/2008JA013580.
- Zong, Q. et al. (2007), Ultralow frequency modulation of energetic particles in the dayside magnetosphere, *Geophys. Res. Lett.*, **34**, L12105, doi:10.1029/2007GL029915.